Re-visit analytic modeling of Angelfish

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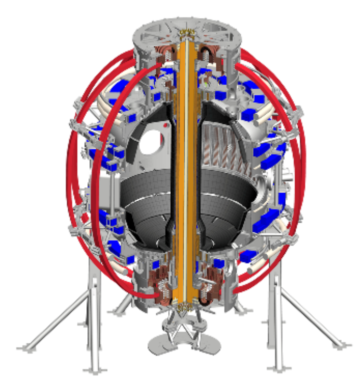


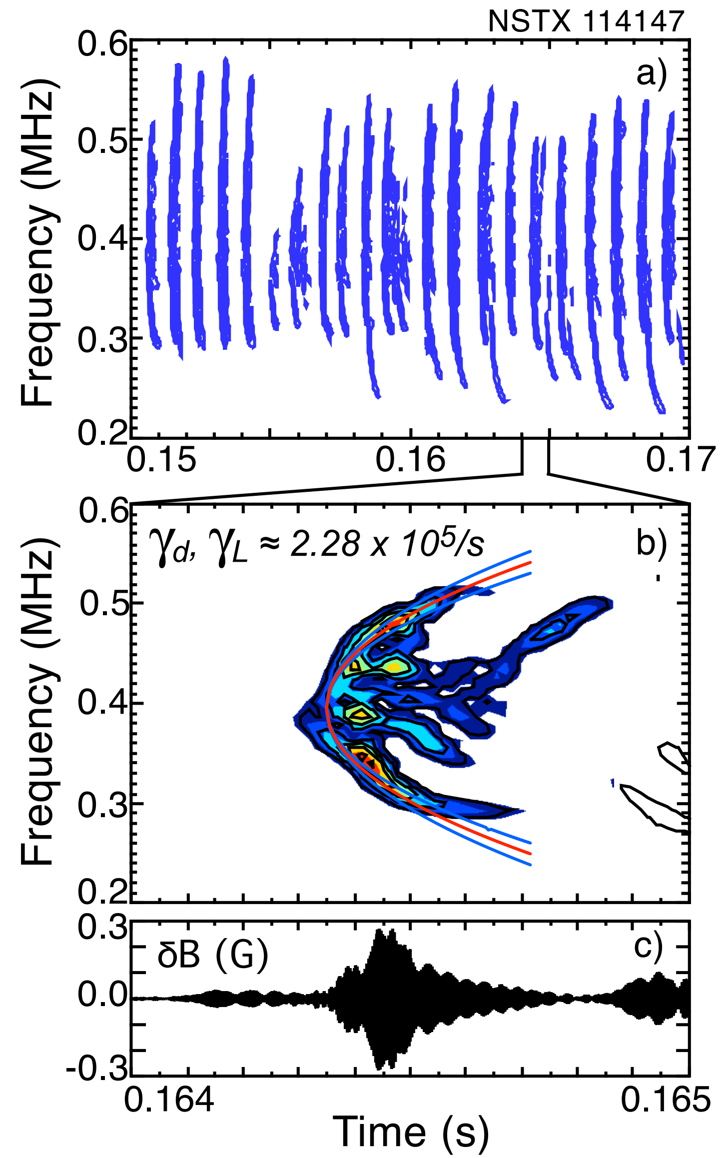
Idea is to restart work on draft paper from 2010

- Paper was an extension of the hole-clump model to “Angelfish”, largely by Nikolai and Herb.
- Work kind of foundered on issue of large orbit (variable ω_{ci}) fast ion interactions with mode.
- Issue is partially alleviated by the apparent observation that resonant fast ions are largely on “stagnant orbits”.
- Also, subsequent studies have shifted probable Angelfish mode i.d. from CAE to GAE.

Angelfish (chirping GAE) observed over wide range of NSTX beam heated plasmas

- An important development since the inception of this paper has been the identification of Angelfish as chirping GAE.
  - further discussion to follow.
- Range of frequency chirp is large - often larger than continuum spacing
  - discussed further below.
- Angelfish seen at toroidal fields from 2.6 kG up to 5.9 kG, with up-down chirps mostly at low field or high beta?
- More complex chirping behavior is also seen, including cases without chirping.
- Evidence of interactions with nearby (in frequency) eigenmodes is also seen.

$I_P \approx 0.7$ MA, $P_{NBI} \approx 4.0$ MW, $B_{tor} \approx 2.55$ kG, $\beta \approx 20\%$



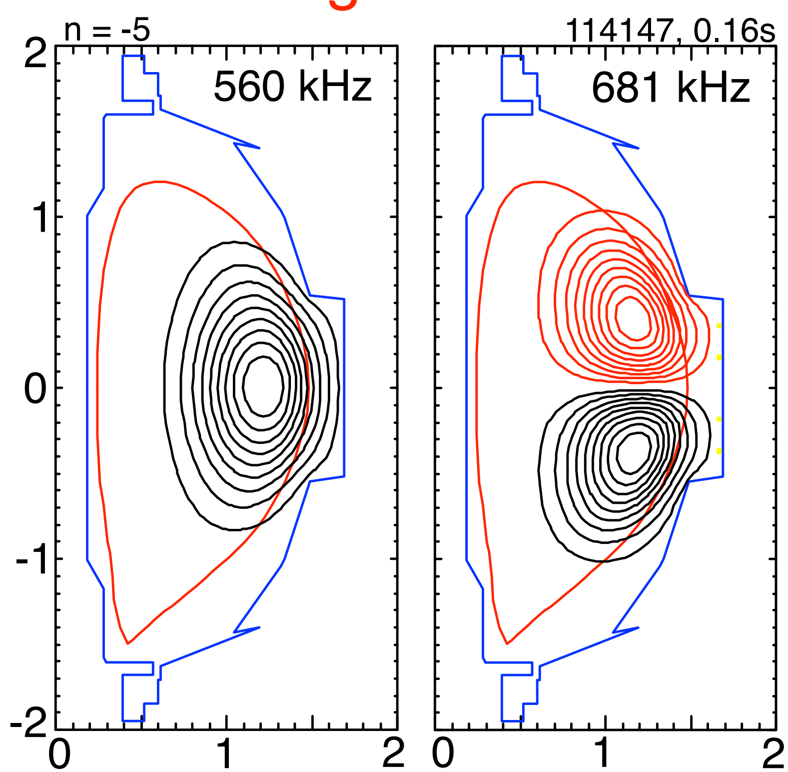
Outline of talk

- Discussion of identification of modes as GAE vs. CAE.
- Examples of asymmetric chirping and more complex behavior.
- Some reflectometer data showing absolute amplitude and possibly some constraints on localization.
- Orbit (SPIRAL) calculations of the resonant population and discussion of the $\omega_{ci}(R)$ problem.

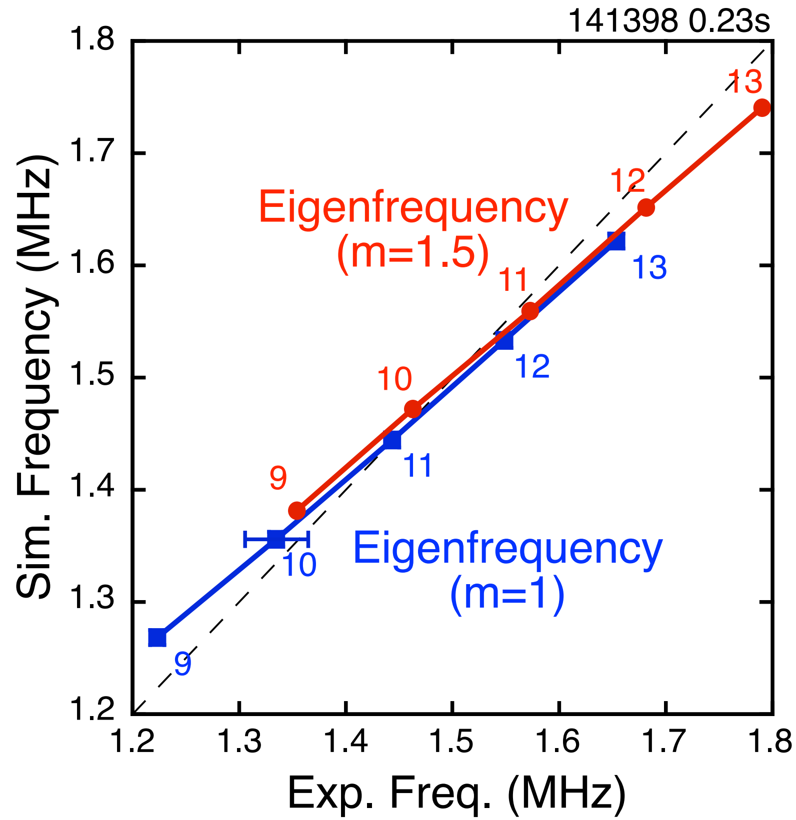
Observed mode frequency too low for CAE?

- CAE eigenmode code does very well in predicting CAE frequencies.
- Much simpler than Håkan Smith's CAE3B, but agrees well in overall mode structure and frequency predictions.

'Angelfish'



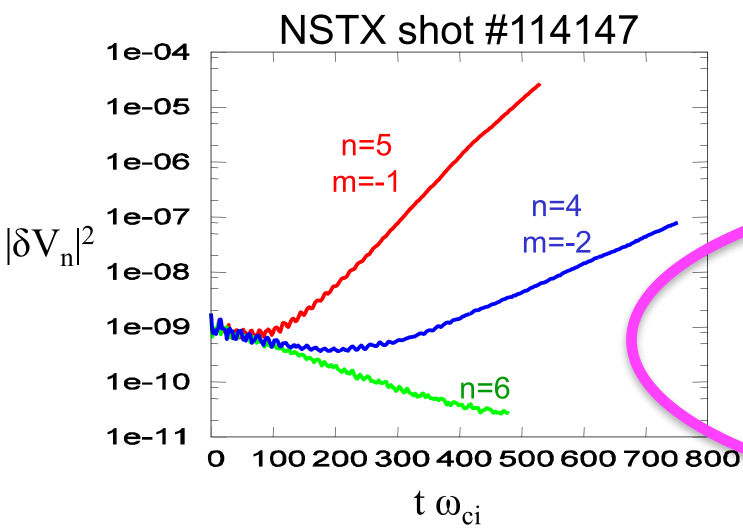
CAE



This slide from Elena's 2010 APS talk

Low-*n* most unstable modes have a character of GAE modes

- Growth rates of unstable modes are very sensitive to details of distribution function (pitch-angle).
- Most unstable mode toroidal number shifts to larger n for larger q_0.



$\gamma_4 = 0.005\omega_{ci}$ and $\omega = 0.3\omega_{ci}$
$\gamma_5 = 0.014\omega_{ci}$ $\omega = 0.3\omega_{ci}$

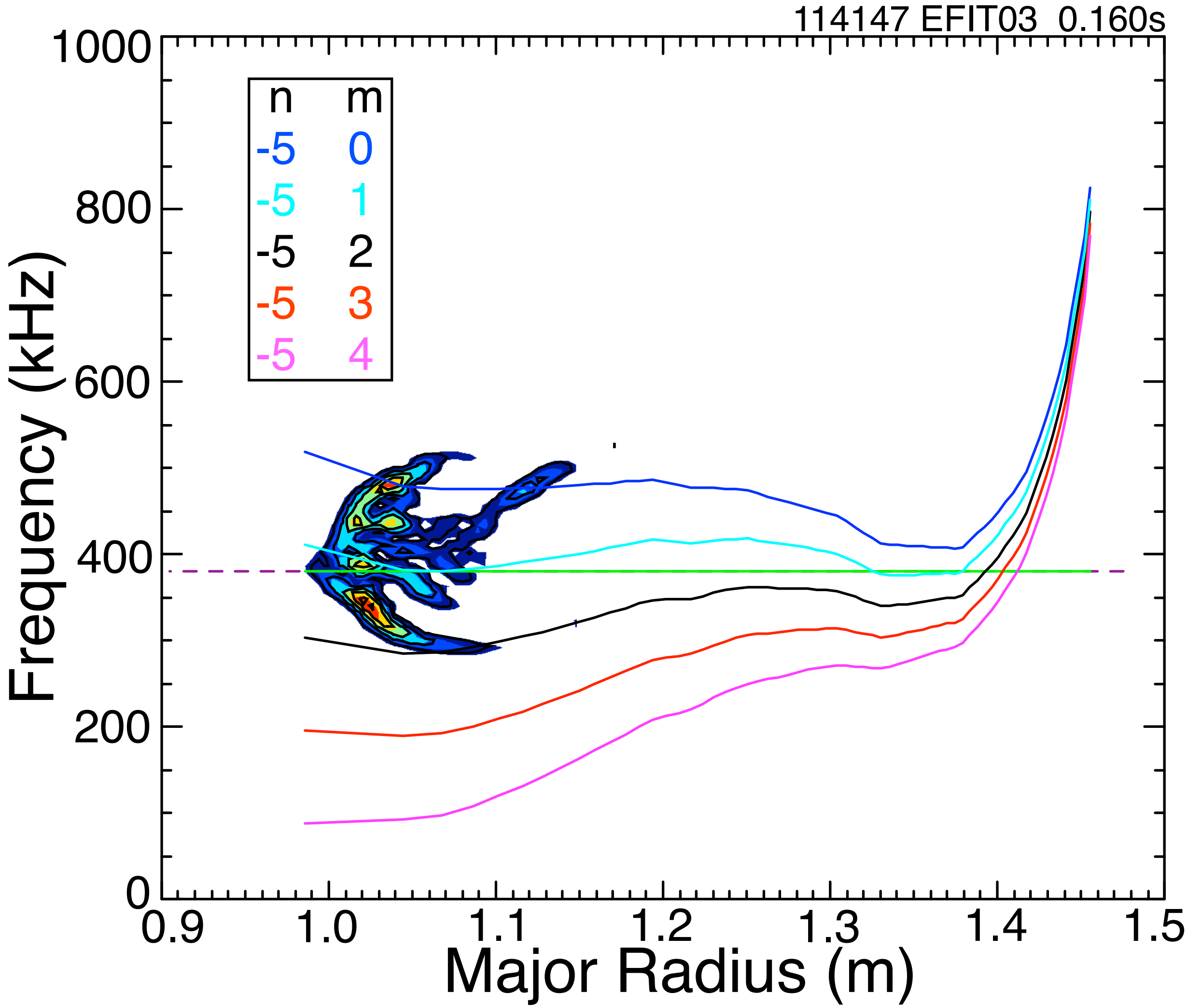
$$k_\parallel = \frac{\omega_{ci} - |\omega|}{v_\parallel}$$

Observed features agree with that of GAE mode, which exists just below the lower edge of the Alfven continuum:
- For each *n*, several *m* are unstable with large $k_{//}$ and $nm<0$.
- Localized near magnetic axis.
- Large $\delta B_\perp$ component in the core.

- Main damping mechanism for GAE is continuum damping (modeled in HYM with artificial viscosity): $\gamma_d/\omega \sim (r/r_{res})^{2m+\delta}$
- Modes with larger-*m* have smaller radial extent.

Chirp range > continuum spacing?

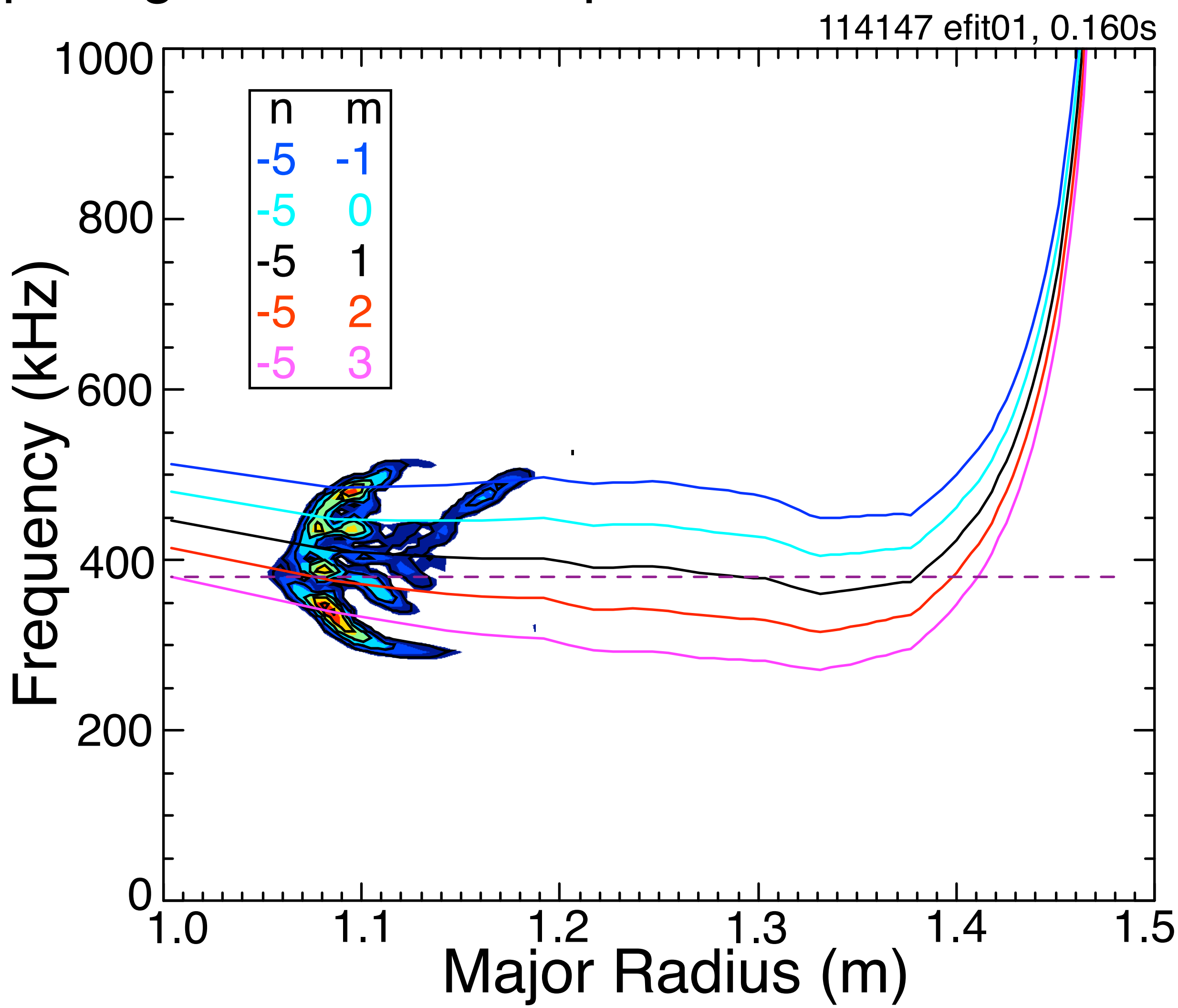
- Wrong helicity (like ICE), but no experimental data.



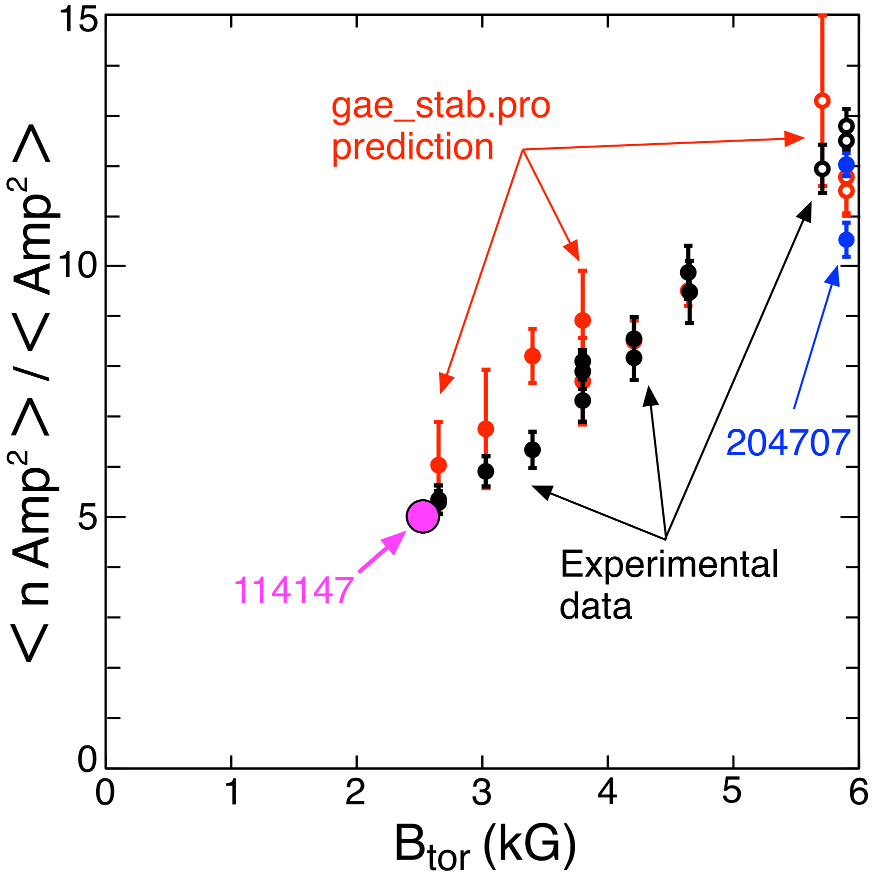
- This EFIT suggests mode localized towards core.
- Poloidal mode # is low - kind of consistent with HYM simulation.
- In core region, chirp range of order twice(?) gap width.
- $f_c = (m-nq)V_{Alfvén}/(qR)$

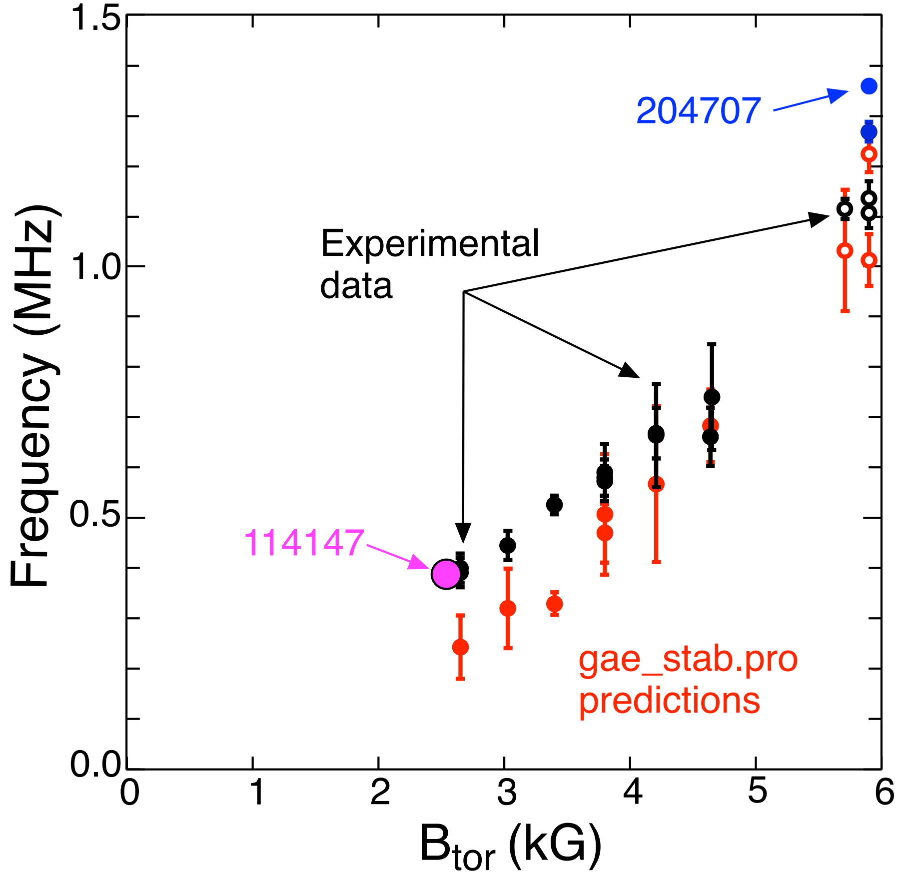
Different equilibrium reconstruction can look very different

- Now chirp range crosses multiple continua



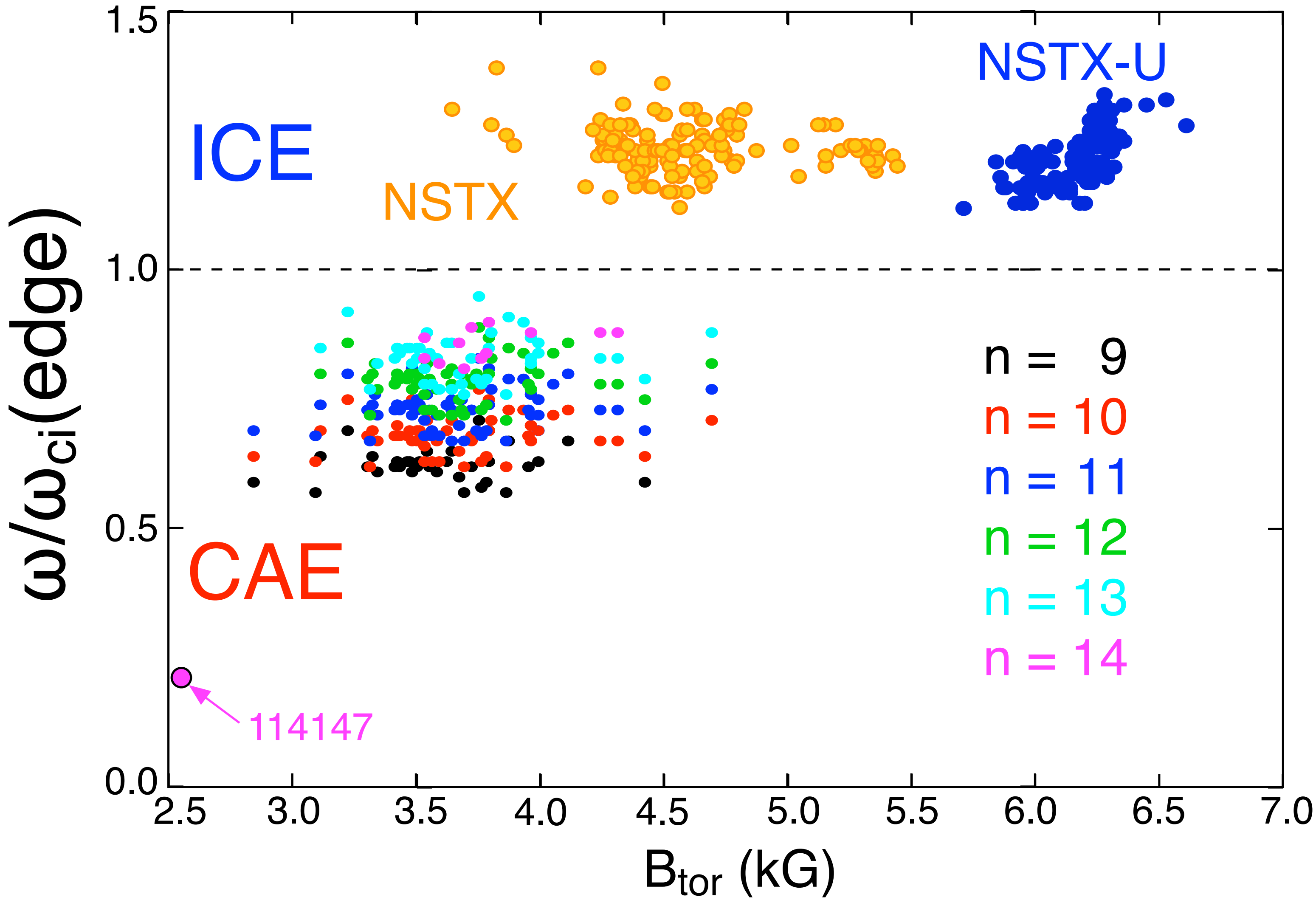
Mode number and frequency consistent with previous GAE scaling studies





- Not proof, but identification as GAE is consistent with dispersion relation calculations

Angelfish frequency not consistent with empirical CAE frequency scaling



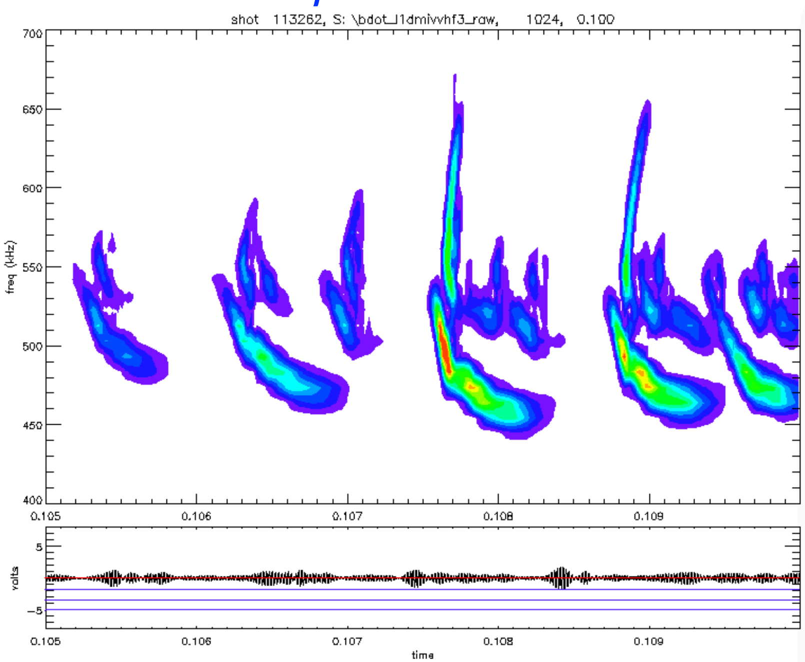
Best bi-frequency chirps at low field or high β

- Anecdotally, the best up-down chirps are in low field shots;
  - However, no extensive study has been done of this, and upward frequency chirps are seen at higher fields.
- At intermediate field, more complex chirping behavior can be found.
- At higher field, chirps are more typically just in the downward direction or up chirps decoupled from down chirps.
- With only down-chirps, often evidence of higher frequency eigenmodes.

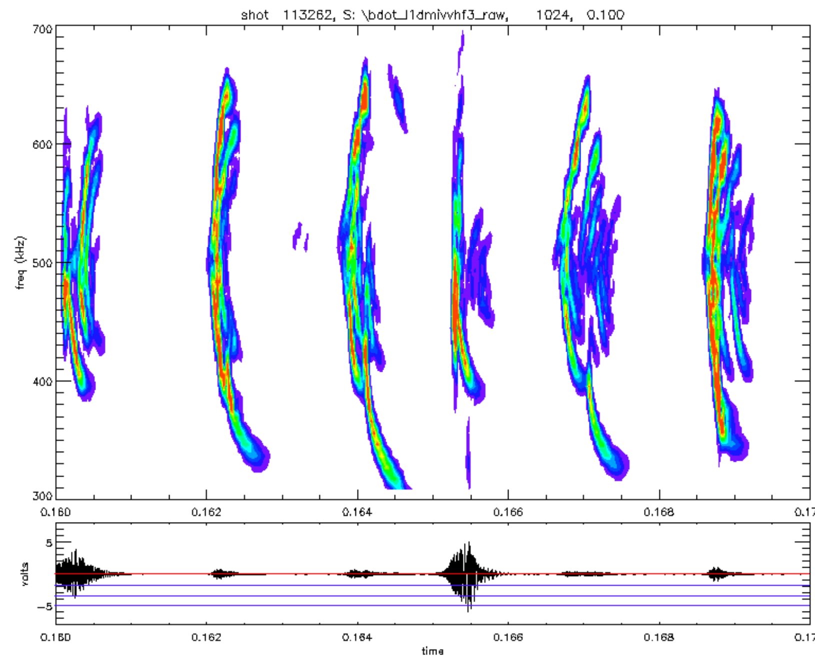
Does symmetry depend on β?

- At low β chirping is more commonly only downwards?
- Up-chirp is much faster than down-chirp at low β.
- Other parameters are also changing, may not be only β.

$\beta \approx 5\%$

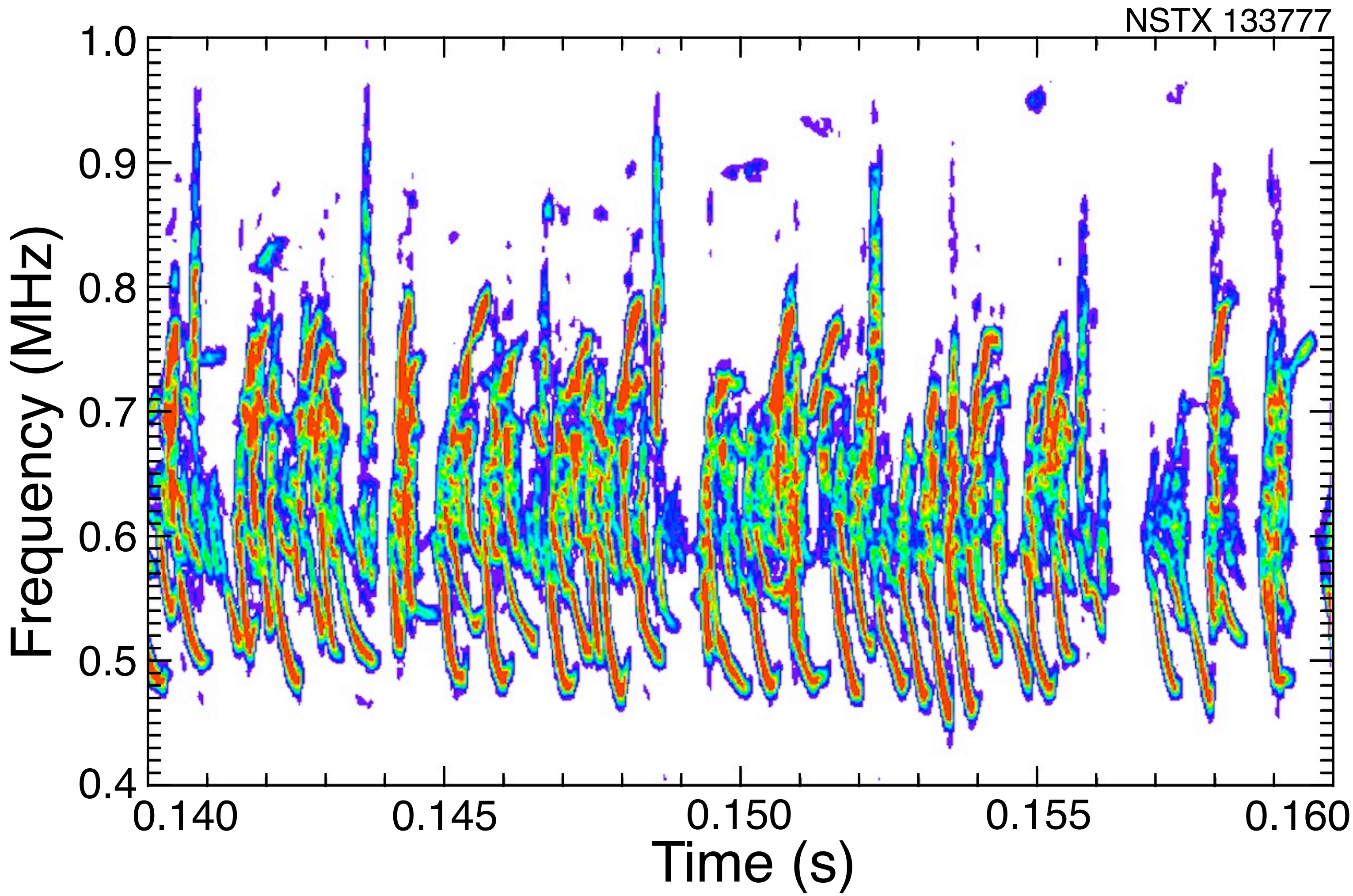


$\beta \approx 15\%$



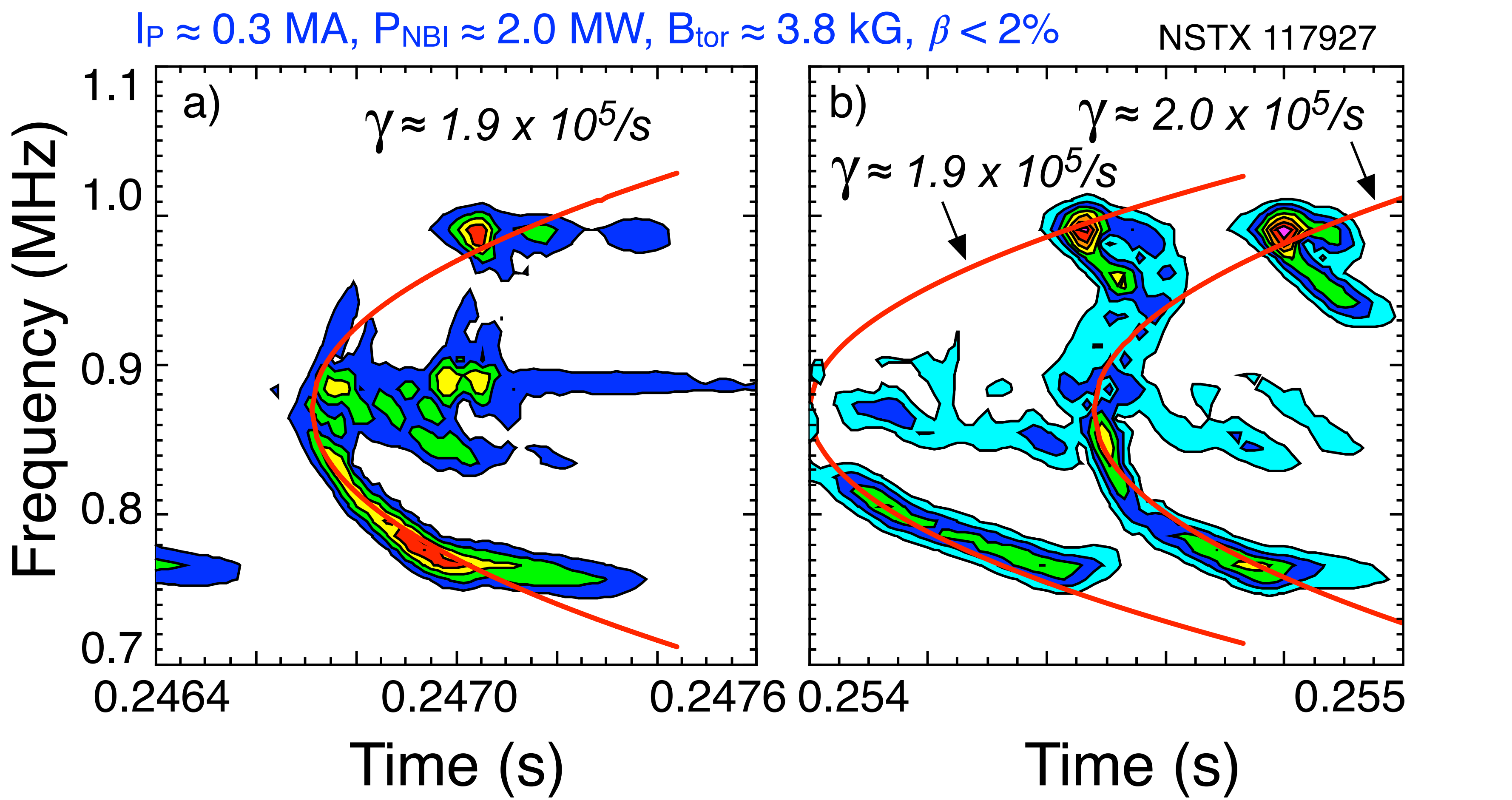
Under some conditions, quasi-continuous chirping is seen

- In this case, there is also some upward chirping.

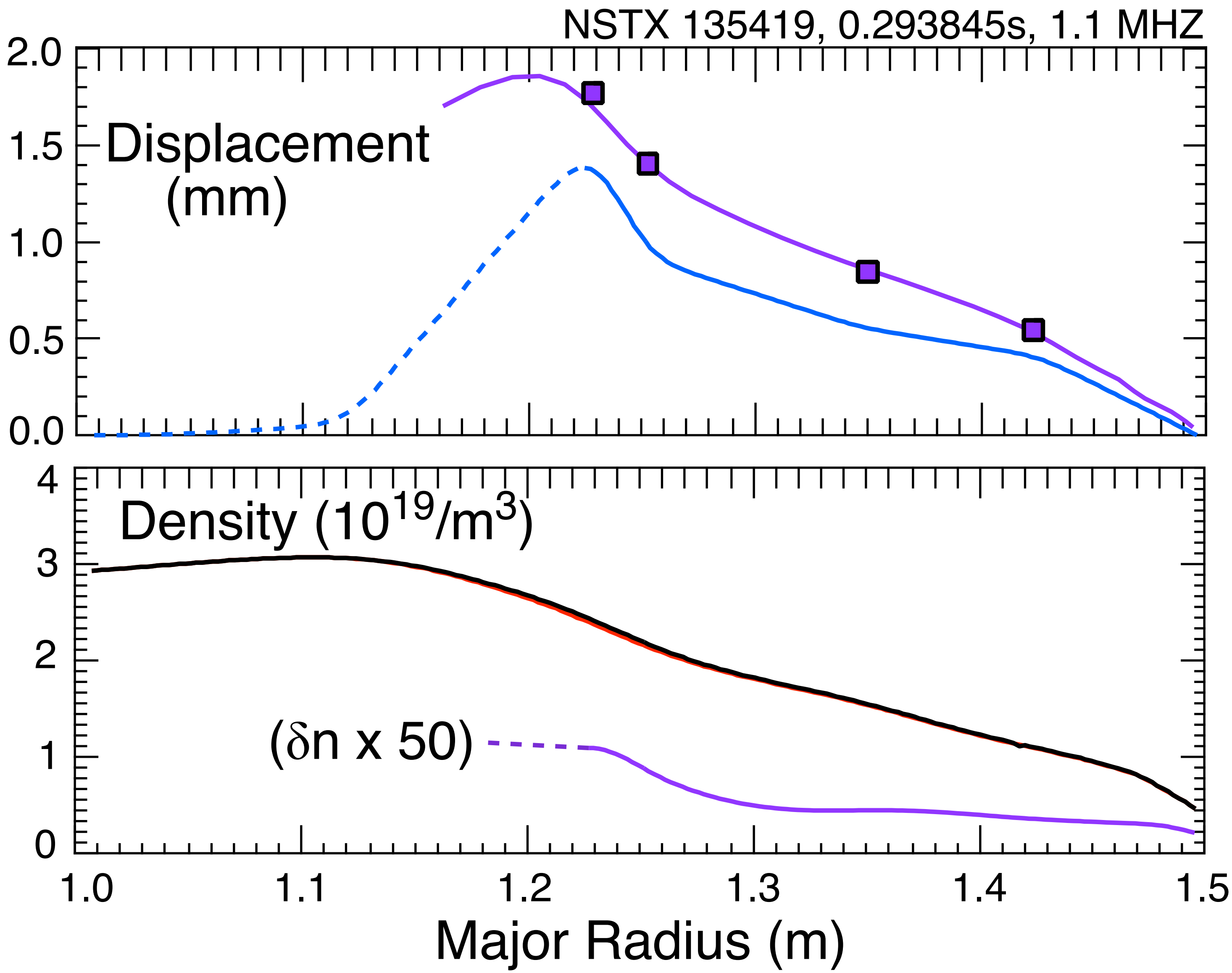


Chirping is often not symmetric

- At higher field, chirping is more typically downward and there is often evidence of nearby modes.



Reflectometer data shows modes peaks towards axis

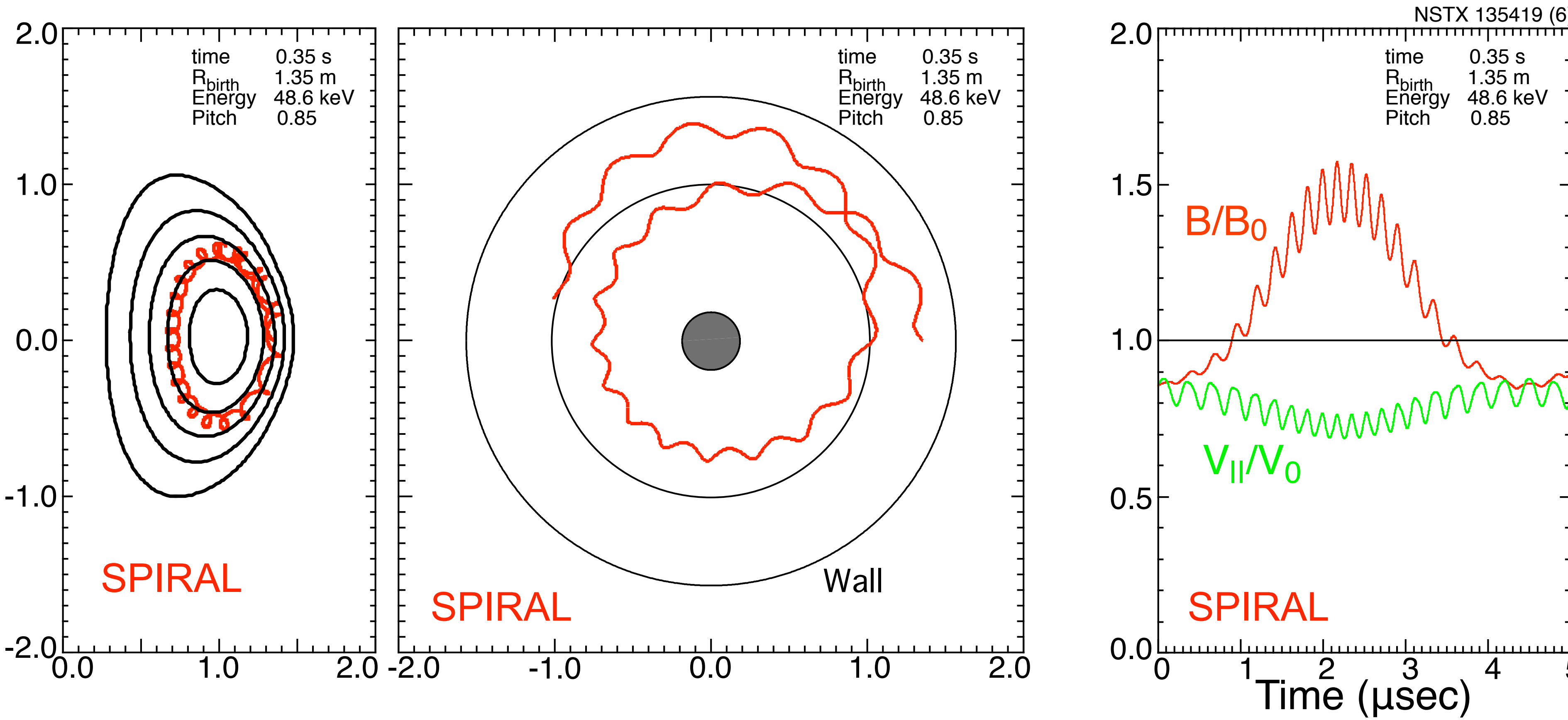


Low aspect ratio means large mod(B) variations over fast ion orbits

- Doppler-shifted resonance means particle moves into and out of resonance over poloidal orbit;
  - more importantly, relative phase between fast ion and mode changes significantly and continuously
  - $V_{||}$ is also changing, a smaller, but reinforcing variation.
- Lower field also means that there are fewer cyclotron oscillations in a toroidal/poloidal orbit.
- However, orbits of fast ions satisfying the resonance constraint tend to be stagnant orbits with much smaller cyclotron frequency variations - coincidental or necessary?
- Experimental observations clearly indicate drive is possible and HYM calculations show that there is drive for GAE.

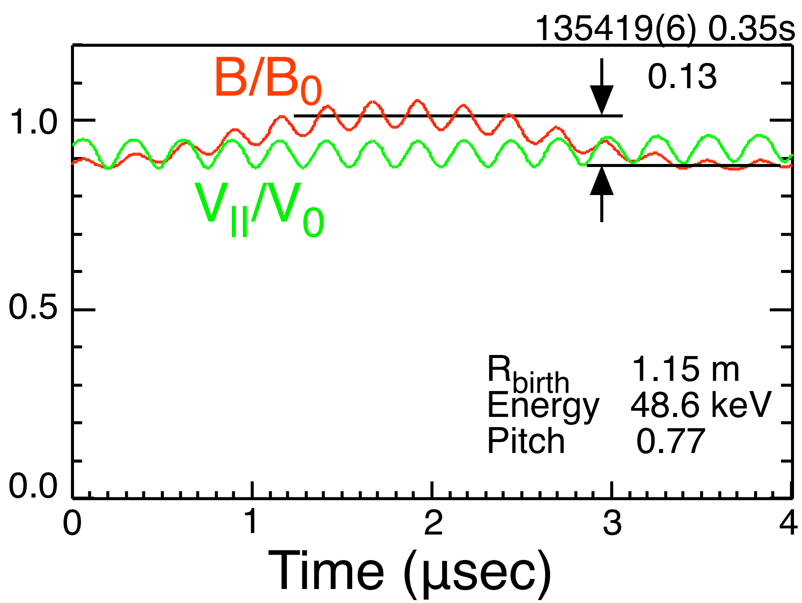
Relatively few cyclotron periods/orbit

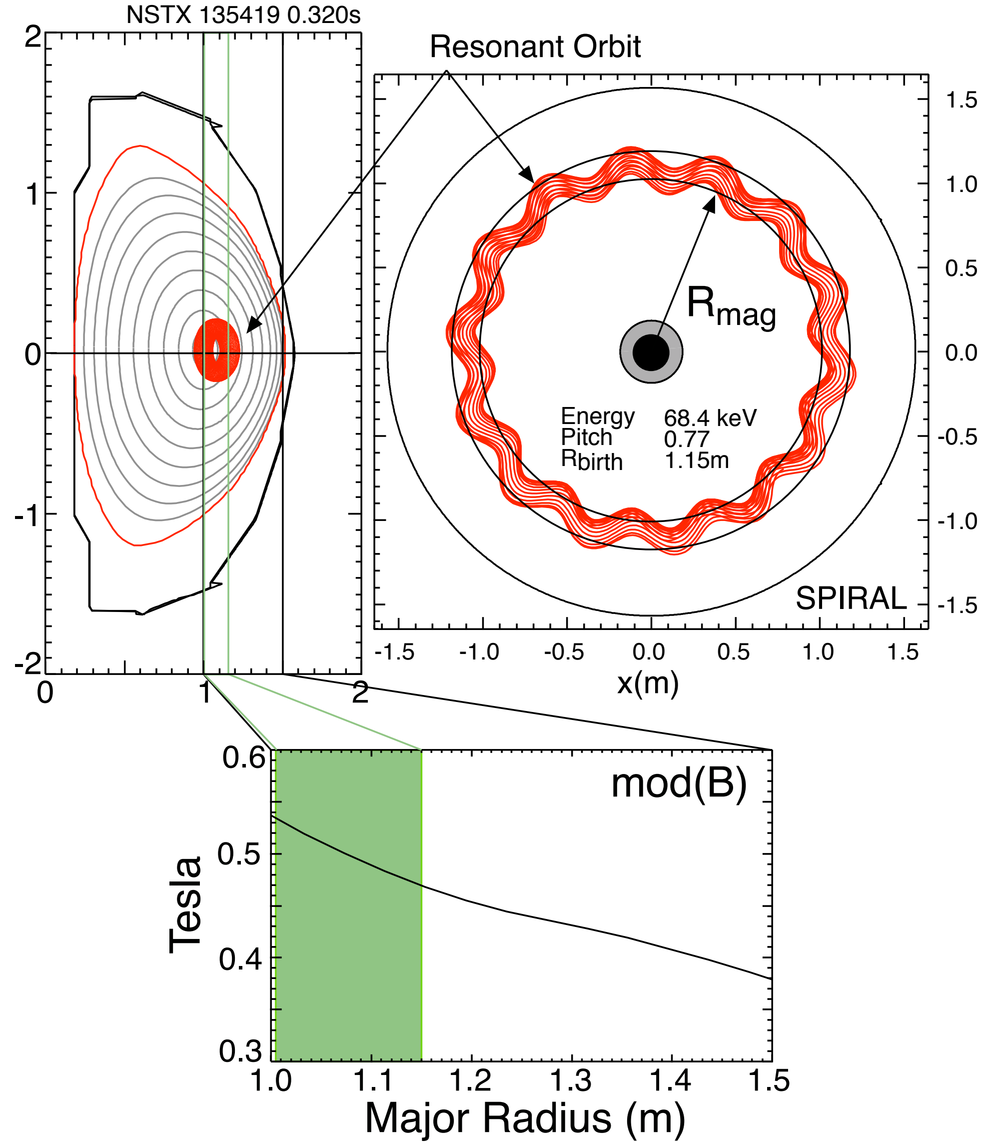
- Even at 48.6 keV and 4.64 kG there are only approximately 15 cyclotron periods per toroidal orbit.
- That can also result in a 50% variation in ω_{ci} and $V_{||}$



In contrast, stagnant orbits have much smaller variation in cyclotron frequency.

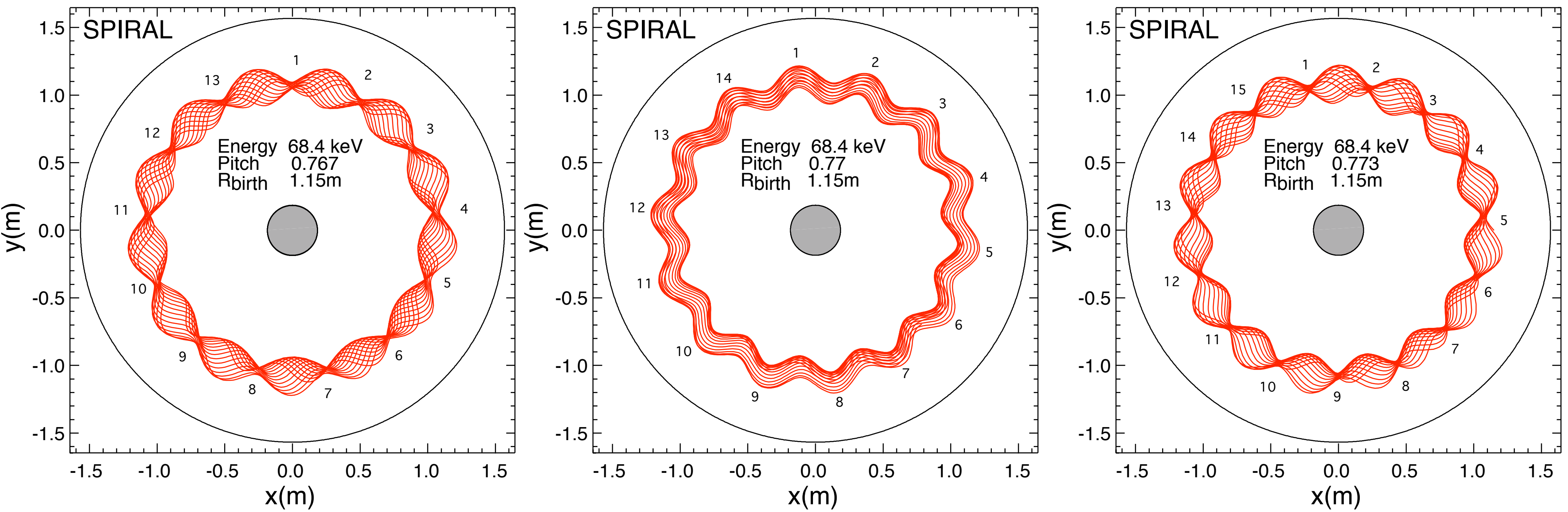
- Even at 48.6 keV and 4.64 kG there are only approximately 15 cyclotron periods per toroidal orbit.
- That can also result in a 50% variation in ω_{ci} and $V_{||}$





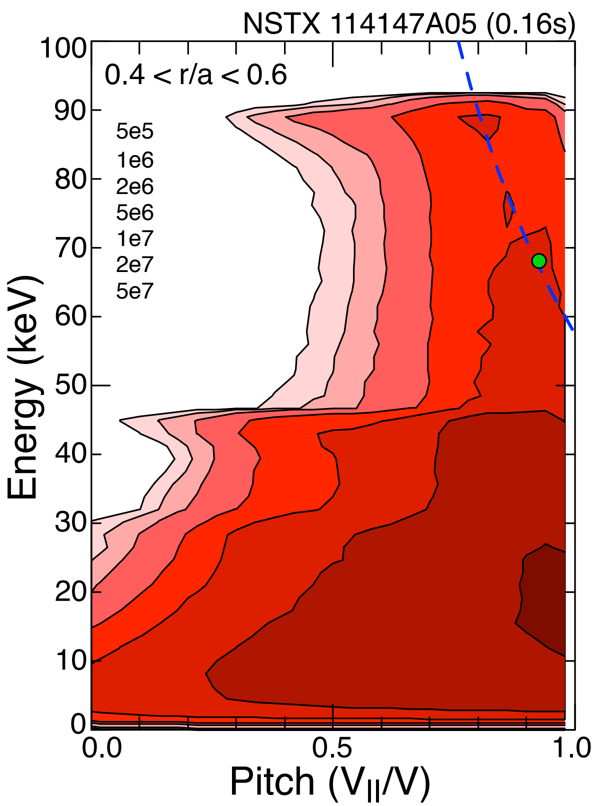
For stagnant orbits, only small change in pitch is needed to change resonance frequency

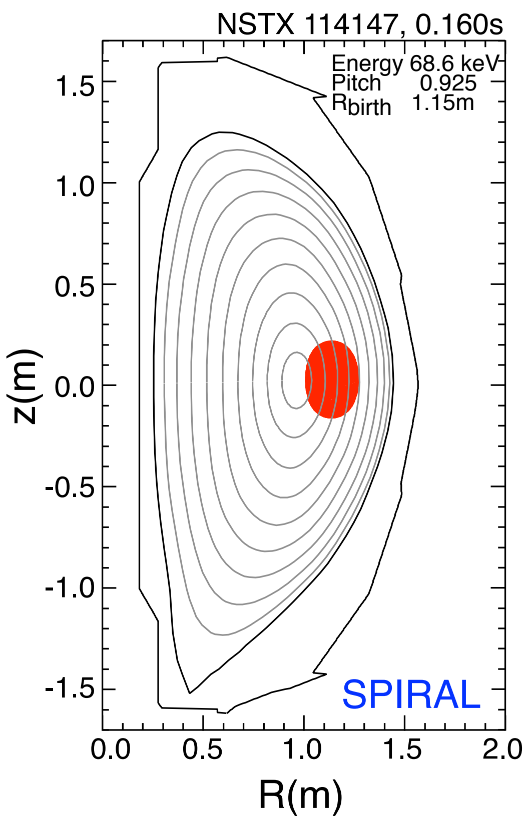
- (not sure what to make of this)

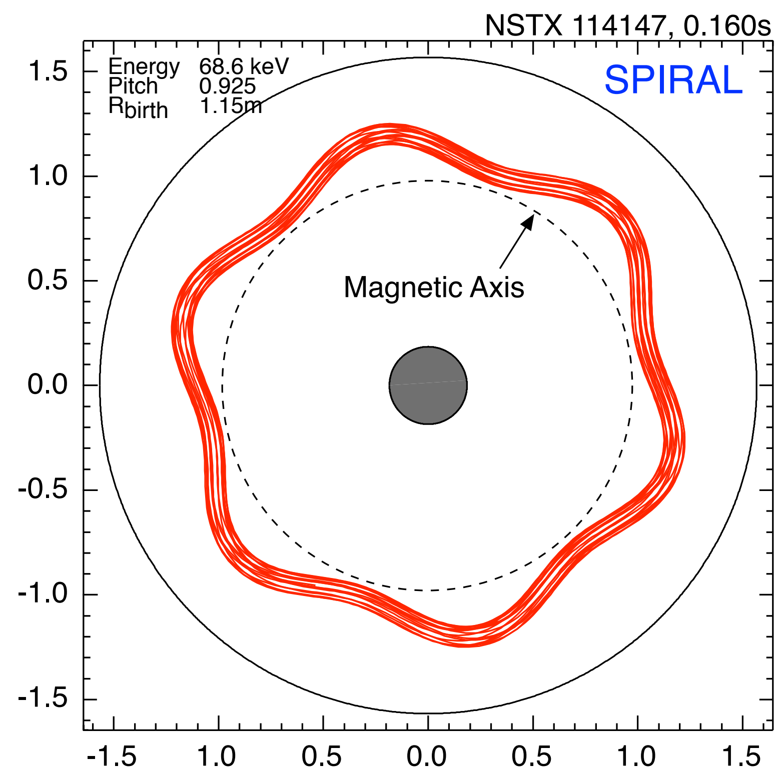


Only 6 cyclotron periods per toroidal transit

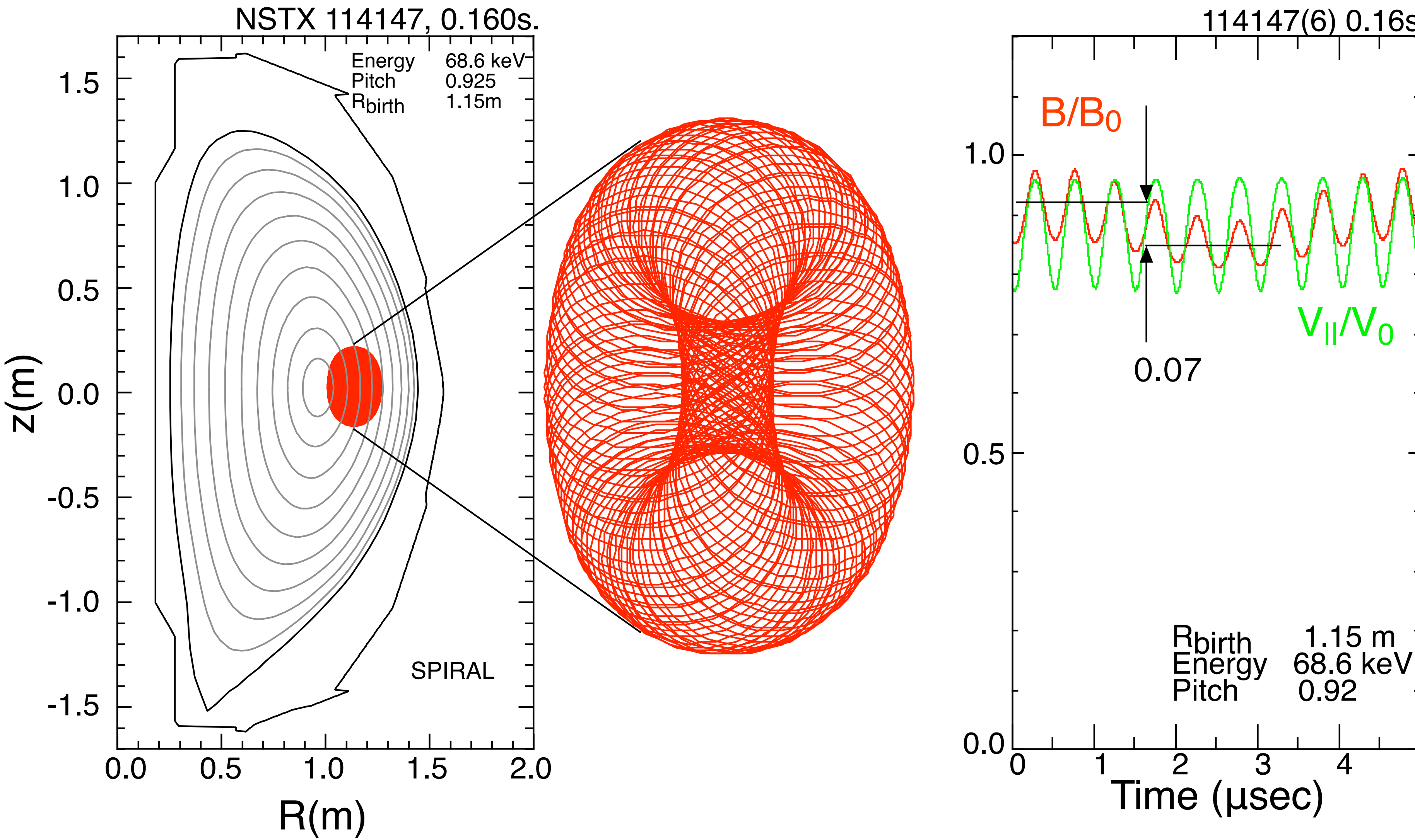
- Situation is ‘worse’ in 2.6 kG cases
- But, SPIRAL calculations find near stagnant, high pitch orbits for fast ions expected to be resonant with GAE.







Small ω_{ci} variation for stagnant orbits



So, the big question…

- Even for stagnant orbits, does the cyclotron frequency change slowly enough so that the resonant ions can still be considered “trapped” in the wave field?
- If the resonant frequency of the fast ions is changing to track the observed mode frequency change, does that imply $V_{b||}$ is changing?
- $\omega_{ci} - k_{||}V_{b||} \approx \omega_{GAE}$